

Reviewing the Literature in Energy Generation using Solid Oxide Fuel Cell: A Complete Bibliometric Study

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Abstract: Determine the different studies that have been published in various journals, countries and researchers and be able to contribute to future researchers who wish to write about Solid Oxide Fuel Cells (SOFC). A bibliometric analysis will be used which will determine the different studies that have been published in various journals, countries and researchers. The main researchers on the subject are the United States and China, indicating that the development and subsequent massive implementation of these cells will come from these countries. The use of solid oxide fuel cells has been carried out by different countries in the world to find a solution to the crisis that exists in the environment, generated by the excessive consumption of fossil fuels.

INTRODUCTION

Solid Oxide Fuel Cell (SOFC) are low-polluting technology to generate electricity electrochemically at high efficiencies; since, its efficiencies are not limited by the Carnot cycle (Singhal, 2007). Only in the last two decades fuel cells has offered a realistic perspective of being commercially viable which is why it is currently the subject of intense research activity. Unlike other fuel cells, SOFC is a solid-state device that operates at elevated temperatures (Ormerod, 2003). The way to produce electricity is through the electrochemical combination of fuel and oxidant gases through an ionic conduction oxide membrane which can be achieved at temperatures of 600-800°C (Choi *et al.*, 2011) which has shown that it reaches temperatures until 900°C (Abdalla *et al.*, 2018). In 1997, the US Department of Energy launched its Vision 21st program, to develop core technologies for a fleet of power plants multi-fuel and

flexible with an electricity generation efficiency of more than 75% for gas and 60% for coal. It was found that the fuel cell is an emerging alternative to traditional power generation systems; since, it reaches this efficiency percentage with lower emissions (Zhang *et al.*, 2010).

An improvement that can be implemented to these fuel cells is to reduce start-up time to implement SOFCs in mobile applications (Spivey and Edgar, 2012). One of the factors that affect durability is the contamination of the cathode by Cr and Si as well as the humidity and CO₂ that are inherent to the ambient air which generates serious problems in the degradation of long-term performance (Yang *et al.*, 2017). A recent study found that solid oxide fuel cells supported by anode accumulate >700 h of stable operation in dry ethanol with high current production (Steil *et al.*, 2017).

Although, economically competitive SOFC systems appear to be ready for commercialization, an extensive inventory of materials and keys manufacturing processes

are needed to improve systems and reduce costs. These needs arise from the demand for industrial SOFC production on a large scale. After observing the above reasons, the average components of a fuel cell, on a large scale has been synthesized using the glycine-nitrate combustion method (Wain-Martin *et al.*, 2017).

SOFCs has a better performance in light hydrocarbon fuels and the use of biogas derived from the Anaerobic Digestion (AD) of the municipal wastewater sludge could provide an opportunity for the CH₄ produced can be used as a renewable fuel. Another objective is to reduce emissions of greenhouse gases (GEI), NO_x, SO_x and hydrocarbons (Lackey *et al.*, 2015).

Recent research on renewable energy has identified fuel cells as an important source of potential energy for the future. Fuel cells are a type of renewable energy that converts the chemical reaction between hydrogen and oxygen to electrical voltage (Ramadhani *et al.*, 2017).

The work process of the SOFC includes, at least, stages of heating, starting, operation and cooling. In the starting process, it must be ensured that the SOFCs operate in a stable state with an external load since the unstable thermal expansion induces a considerable loss of energy (Niu *et al.*, 2017).

Nano technology is generating a lot of attention these days and therefore has generated considerable expectations not only in the academic community but also among investors, governments and industry (Serrano *et al.*, 2009) in the field of fuel cells, is used for development and therefore improves performance in the SOFC. The high operating temperature of the SOFC (700-900°C) has shown serious disadvantages concerning its overall performance and durability. Therefore, the operating temperature has been reduced to an intermediate temperature range of approximately 400-700°C which improved performance and subsequently commercialized SOFC as portable energy sources (Abdalla *et al.*, 2018).

Advanced energy analysis is performed for a solid oxide fuel cell with anodic gas recirculation. For this, the inevitable conditions are specifying the most important electrochemical parameters that result in the best possible performance. It is noted that, under the unavoidable circumstances, the efficiency of the energy of the fuel cell can be 32% higher and the destruction of energy can be 38% lower, compared to the corresponding values under real conditions (Fallah *et al.*, 2017).

The microstructural properties such as the relative density, the length of the triple phase boundary, the specific surface area, the tortuosity factors, are calculated for analysis and modeling based on solid oxide fuel cell microstructures (Yan *et al.*, 2017).

This article presents a bibliometric analysis of research about SOFC. The main objective of this study is to identify some of the most relevant researches in this

field and some of the most recent trends according to the information found in the Web of Science database (Mreigo and Yang, 2017).

MATERIALS AND METHODS

Bibliometric analysis: Bibliometric analysis is a guide that can quantify the evaluation of scientific publications to identify particular points of investigation (Jacobs, 2010). The tools used by the bibliometric analysis to measure scientific progress in various fields are mathematics and statistics, to investigate mathematical regularities, variable patterns and quantitative management of the information studied (Hou *et al.*, 2015; Zhang *et al.*, 2015). Bibliometrics is a subdiscipline of scientometrics whose purpose is to provide information about the results of the research process, its volume, evolution, visibility and structure. In this way, assess scientific activity and the impact of both research and sources.

Impact factor and h-index: The impact factor is a measure of the importance of a scientific publication. It is calculated each year by the Institute for Scientific Information and published in a dating report called Journal Citation Reports (JCR). It is calculated by dividing the total citations of documents of a journal published in the 2 previous years cited in the (JCR) by the total number of documents published in that journal in the same previous periods. The impact factor has been used to evaluate the quality of researches and researchers that have been published by different journals (Mao *et al.*, 2015). In this study, the impact factor will be used to rate the influence of some journals in 2017.

Proposed by Hirsch in 2005, h-index is another indicator to assess the achievement of a scholar's research of both quality and quantitative aspects (Hou *et al.*, 2015; Hirsch, 2010). According to Hirsch (2010), the definition of h-index is that a researcher with an index of h has published h articles, each of which has been cited in other documents at least h times. In this study, h-index was used to evaluate the influence of journals, countries, researchers and institutes.

Social Network Analysis (SNA): The concept of social network, according to science, refers to a finite set of actors and the relationships that exist between them or that link them, likewise, social networks are considered social structures where are produced processes of communication and transaction between people take place. Thus understood, there is evidence of the existence of social networks that go back thousands of years ago in history, together with the formation of the first human communities. Social Network Analysis (SNA) is a quantitative approach that is used to rate the

relationship between social actors (Hou *et al.*, 2015). SNA has been widely applied due to the development of network theory and computer processing capabilities (Ye *et al.*, 2012). In this study, SNA was used to investigate academic collaboration between the most productive countries/territories and institutes.

Data source: The Institute of Scientific Information (ISI) Web of Science (WoS) published by Thomson Reuters is a platform that stores the references of the main scientific publications of any discipline of knowledge (Chadegani *et al.*, 2013). As a database widely accepted by different scientific fields, WoS has been considered as an important source of data for bibliometric analysis (Van Leeuwen, 2006). WoS could provide more uniform and standardized records compared to other databases such as Scopus (Hou *et al.*, 2015; Battencourt and Kaur, 2011). Falagas *et al.* (2008) found that WoS is an excellent tool to develop good graphics and detailed citations analysis.

RESULTS AND DISCUSSION

Among 1922 publications obtained from the WoS database, 97.2% were published in English, followed by Chinese (1.6%) and Spanish (0.5%). Only those articles published in English (1869 publications) are taken into account for this study because English is the common academic language throughout the world. Among them, article (1593 publications) and articles in process (242 publications) are the main contributions, which represent approximately 82.9 and 12.6% of the total literature published in English, respectively. Furthermore, other contributions include meeting abstract (1.5%), review (1.5%), news item (0.5%) and correction (0.5%) which are insignificant. Therefore, 1835 publications (i.e., research articles and procedural articles) were finally selected for more analysis in this study.

Table 1 tells us that the number of publications related to SOFC grew by 1% from 2007-2011. The average number of researchers for each publication improved from 4.22 in 2007 to 4.68 in 2017 and citations referenced for each publication increased from

21.80 in 2007 to 39.42 in 2017. This indicates that communication and collaboration among the researchers increased.

Table 2 shows the top 10 of the most important journals on the topic of Solid oxide fuel cell. It also shows the number of publications that each journal has made with respect to this topic, the impact factor (2016) of each of the journals and the h-index of them. The table is commanded by the International Journal of Hydrogen Energy with 271 publications on the theme of Solid Oxide Fuel Cell. The second magazine with the most publications is Journal of Power Sources (163), this magazine had the highest number of impact factor (6,395) and also the largest h-index (237).

Figure 1 shows the global distribution of publications related to SOFC from 2007-2017, covering 68 countries in total; This distribution is given by different colors for a specific range of publications in each of the different countries that have studied on this topic. Also, we can see the h-index of the 10 countries with the highest rate, these countries are: USA, China, Japan, Italy, Germany, France, South Korea, United Kingdom, Canada and Spain.

Table 3 shows the performance of the ten most productive countries with publications referring to This Topic (TP), also shows the percentage of total publications (TP R) and the h-index of these same countries (Fig. 2).

Research hotspots

The most frequently cited papers: Although, several misquotes may arise, the variation of annual citations may be used to assess the academic influence of publications

Table 1: Primary performance of SOFC publications from 2007-2017

Years	Publications	Researchers/publications	Referenced publications
2007	184	4.22	21.80
2008	192	4.33	21.84
2009	182	4.35	26.97
2010	154	4.24	24.99
2011	204	4.37	25.95
2012	187	4.28	28.77
2013	189	4.48	33.65
2014	153	4.68	34.29
2015	152	4.49	33.70
2016	160	4.77	36.79
2017	164	4.68	39.42

Table 2: Characteristics of the top 10 of journals from 2007-2017

Journals	Amounts	Percentage	Impact factor	h-index
International journal of hydrogen energy	271	14.1	3.582	165
Journal of power sources	163	8.5	6.395	237
Journal of the electrochemical society	148	7.7	3.259	226
Solid state ionics	136	7.1	2.354	164
Fuel cells	106	5.5	1.706	57
Journal of fuel cell science and technology	70	3.6	0.817	29
Ceramics international	47	2.4	2.986	77
Journal of alloys and compounds	37	1.9	3.133	133
Electrochimica acta	36	1.9	4.798	192
Abstracts of papers of the american chemical society	29	1.5	NA	NA

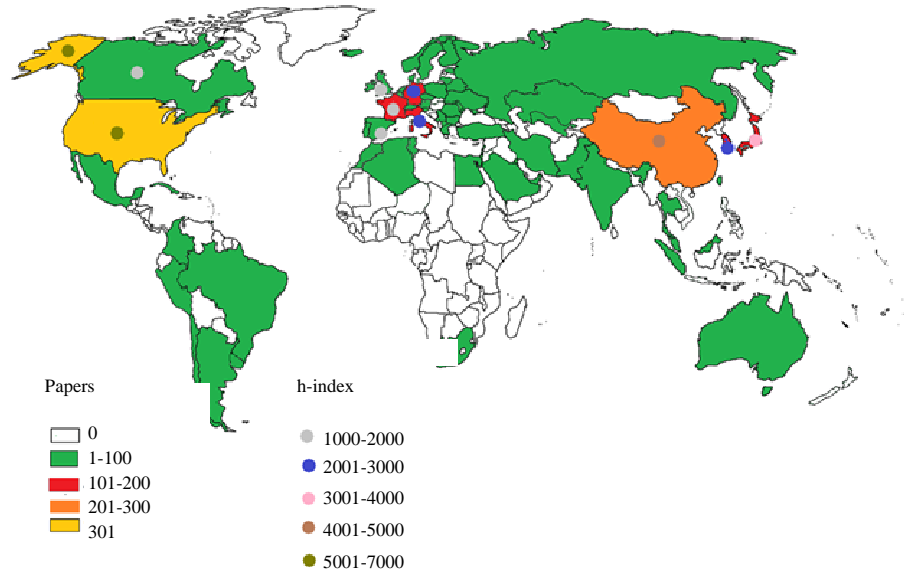


Fig. 1: Global distribution of SOFC publications

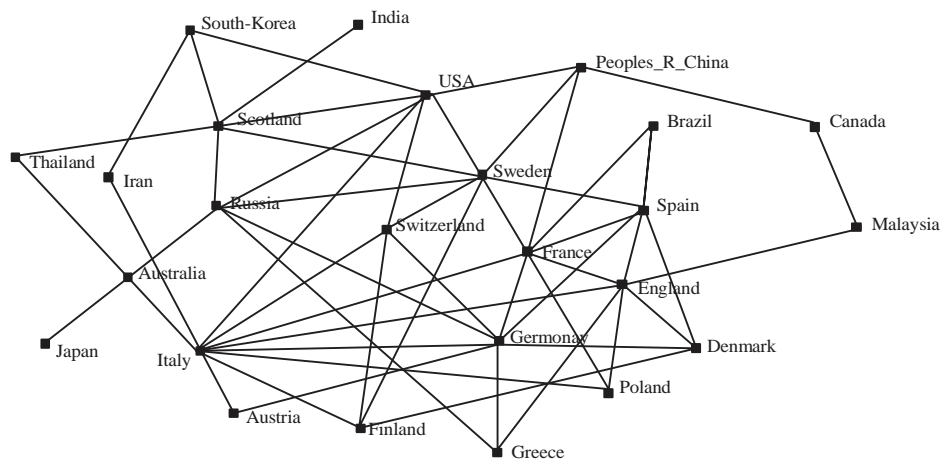


Fig. 2: The cooperation network of the 25 most productive countries

Table 3: Characteristics of the ten most productive countries

Countries	TP	TP R	h-index
USA	301	15.7	6578
China	282	14.7	4393
Japan	180	9.4	3024
Italy	158	8.2	2446
Germany	149	7.8	2849
France	137	7.1	1969
South Korea	132	6.9	2172
United Kingdom	99	5.2	1987
India	85	4.4	686
Canada	73	3.8	1560

are lower than those published in previous years which is very sensible, since, these documents may not adequately address attentions due to their shorter publishing time.

Table 4 presents the main characteristics of the top 10 of the most cited documents. Spinel coatings on ferritic stainless steels for SOFC interconnect applications is the most cited with 37 citations, followed by Reduction of chromium vaporization from SOFC interconnectors by highly effective coatings (31) and high-performance SOFC Cathodes prepared by infiltration (28). The contribution of the Spinel coatings on ferritic stainless steels for SOFC interconnect applications was to achieve an improvement in electrical performance and resistance to oxidation by applying the spinel coating MnCoO₄ in AISI4 which contains only 17 % Cr and a greater amount

(Mao *et al.*, 2015; Li *et al.*, 2011). Figure 3 shows the total citations and citations of the most frequently cited publications in each year from 2007-2017. It can be seen that the total citations of articles published in recent years

Table 4: Characteristics of the top 10 of the most cited publications

Local citations	Articles	Journals	References
37	Spinel coatings on ferritic stainless steels for SOFC interconnect applications	International journal of hydrogen energy	Yang <i>et al.</i> (2007)
31	Reduction of chromium vaporization from SOFC interconnectors by highly effective coatings	Journal of power sources	Stanislowski <i>et al.</i> (2007)
28	High-performance SOFC Cathodes prepared by infiltration	Advanced materials	(Lee <i>et al.</i> , 2009)
27	Metallic interconnects for SOFC: characterisation of corrosion resistance and conductivity evaluation at operating temperature of differently coated alloys	Journal of power sources	Fontana <i>et al.</i> (2007)
25	Modeling of a SOFC fuelled by methane: From direct internal reforming to gradual internal reforming	Chemical engineering science	Klein <i>et al.</i> (2007)
24	Recent development of SOFC metallic interconnect	Journal of materials science and technology	Wu and Liu (2010)
23	Recent progress in SOFC anodes for direct utilization of hydrocarbons	Journal of materials chemistry	Gross <i>et al.</i> (2010)
23	An analysis of SOFC/GT CHP system based on exergetic performance criteria	International journal of hydrogen energy	Akkaya <i>et al.</i> (2008)
21	A strategy for achieving high performance with SOFC ceramic anodes	Electrochemical and solid state letters	Gross <i>et al.</i> (2007a, b)
20	Thermal stress analysis of a planar SOFC stack	Journal Of Power Sources	Lin <i>et al.</i> (2007)

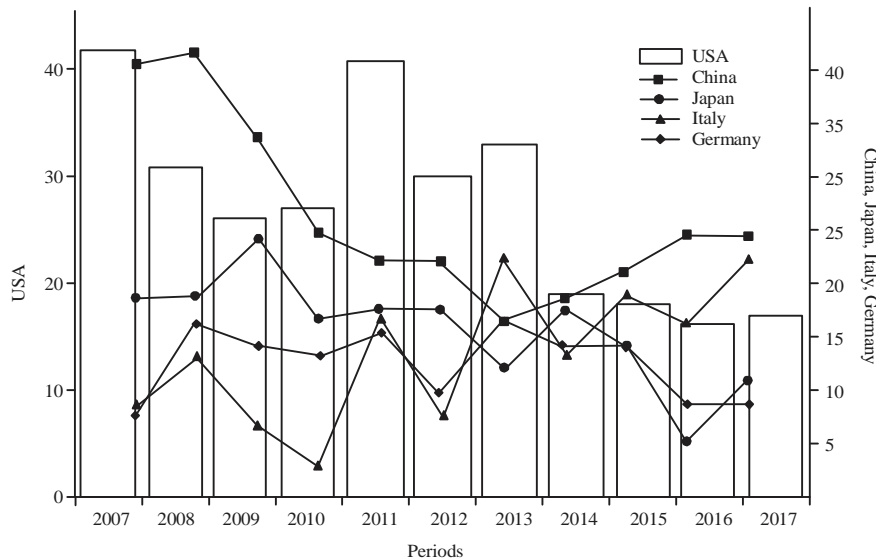


Fig. 3: Annual publications of the top 5 most productive countries

of residual Si (Yang *et al.*, 2017). In the article reduction of chromium vaporization from SOFC interconnectors by highly effective coatings (Stanislowski *et al.*, 2007) it was discovered that the elements Co, Ni or Cu are identified as promising and economical coating materials for metal interconnectors. Since, the metal coatings and their oxides effectively reduced the growth of oxide scale on the steel substrate and showed negligible vaporization rates for Co, Cu and Ni. The magazine most related to the topic of proton membranes is journal of power sources which published 2 of the 5 most cited articles (Fig. 4 and 5).

Main research fields: In this study, the keywords of publications related to SOFC SE were analyzed to identify the research focus of an article (Hou *et al.*, 2015). Of the 20095 words that were analyzed in this study, 2787

keywords were found, being SOFC, anode, delta, cathode and performance the most used by the authors. SOFC appears in the 1922 articles analyzed in this study, while anode and delta were written in 305, 251 articles respectively. It was found that performance is the one that most relates to the other keywords.

The high efficiency and good environmental performance mean that the aeronautical industry is set in two types of fuel cells, the PEMFC and the SOFC, for use in the next 10-20 years (Eelman *et al.*, 2004). The Australian company ceramic fuel Cells successfully achieved an efficiency of a SOFC device up to the theoretical mark of 60% in 2009 (Neilson, 2009; Nagel, 2008) which makes the automotive field also interested in SOFCs for power production auxiliary in vehicles, due to its high efficiency and high working temperatures.

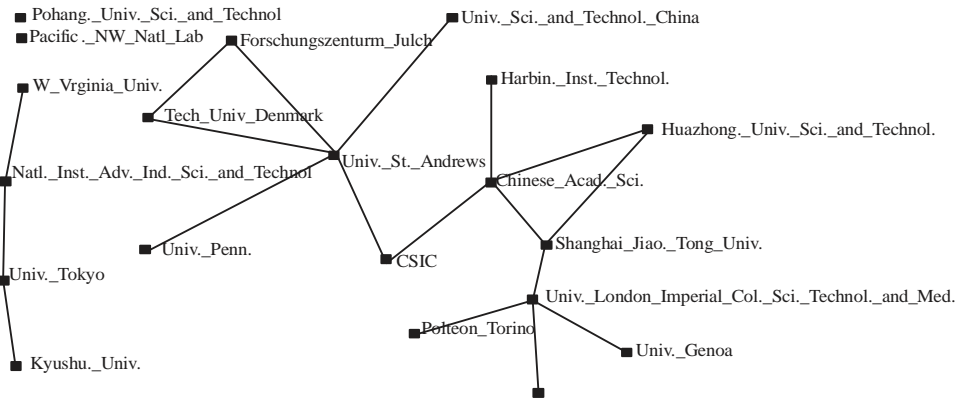


Fig. 4: The cooperation network of the 20 most productive institutions

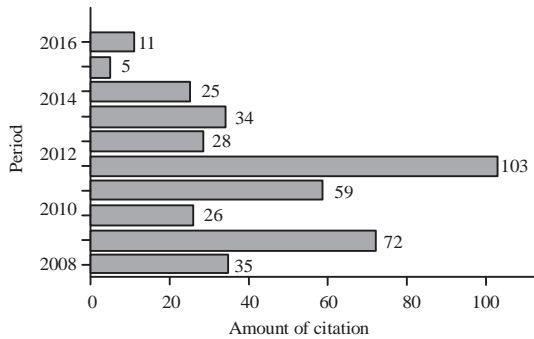


Fig. 5: The total citations and annual citations of the most frequently cited publications from 2007-2017

Another advantage of SOFCs is waste management, less disposition to landfills, the saving of considerable municipal fields for other human activities and a considerably lower environmental impact. What makes the air conditioning industry for hotels, resorts, hospitals, etc. Use SOFCs to produce power in an absorption chiller (Rokni, 2007).

CONCLUSION

To summarize the research and provide future research directions, a bibliometric analysis of the publications from 2007 to 2017 was made to describe the characteristics of SOFC-related documents, to recognize global research foci, and to forecast future directions of research. The results show that the majority of studies related to SOFC are focused on the field of Mechanical Engineering, physical and theoretical chemistry, being international journal of hydrogen energy the most influential journal in the subject developed. Furthermore, the countries that most contributors are the United States and China. These results will be beneficial to provide references for future researchers related to SOFC.

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